2

STUDIES OF HELICOPTER CHARGING

FINAL REPORT

TASK 1

Contract N00014-87-K-0783

ELECTRICAL HAZARDS TO AIRBORNE OPERATIONS

for
The Applied Research and Technology Directorate
The Office of Naval Research

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Abstract

Helicopters hovering above the earth often acquire large electrical charges which can be dangerous to ground personnel who come in contact with the aircraft. In tests of ground-based CH-53E helicopters isolated from earth by insulating pads, potentials in excess of 40 kV relative to the earth were developed after the rotors began to turn. Although the common view is that the electrification is caused by collisions between the rotor and atmospheric dust particles, during this study strong electrification was observed in the absence of any appreciable dust. Charging currents of up to 12 μA were observed in clean air measurements when the helicopter rotor turned and caused strong downdrafts.

Measurements in this study show that an important source of aircraft charging is the current that flows in the hot, electrically-conductive exhaust gases under the influence of the local electric fields. This current was successfully reduced by control of the electric fields acting on the exhaust gases immediately after their emergence from the engine while they were still conductive. Control of these fields required the use of electrostatic shields around the exhausts to reduce the strength of external fields together with the creation of the appropriate internal fields by application of voltages to electrodes within the shields. This technique, applied through a servo controller that was driven by a sensor of the helicopter potential, allowed the export (through the exhaust gases) of undesired charges on the airframe. It also worked well in eliminating charge when the helicopter operated in a dusty environment.

While a useful technique for controlling the charging of helicopters has been developed and tested, more extensive measurements of the factors that control its operation are needed so that an airworthy system can be designed and built.

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OVERVIEW AND RECOMMENDATIONS

TECHNICAL OBJECTIVES:

1. To determine the causes for the electrification of hovering, heavy-lift helicopters.
2. To devise effective, practical means of controlling or eliminating the tendency of a hovering helicopter to acquire large electrical charges which are hazardous to the ground personnel contacting the aircraft.

APPROACHES

1. Study the processes by which charges are transferred to or from an isolated helicopter with particular attention to be given to charging by electric currents flowing in the exhaust gases and by collisions of the rotor with dust particles.
2. Determine the electrical characteristics of heavy-lift helicopters and learn how they charge naturally.
3. Examine the utility of controlling helicopter charging by varying the electric fields that act on the engine exhaust gases.

WORK ACCOMPLISHED

1. Measurements were made of the natural charging of six different CH-53E helicopters that were operated on the ground but isolated electrically from the earth. Under the influence of the local atmospheric electric fields, all of the aircraft charged weakly when the rotor was stationary and strongly when the rotor created a downdraft both in clear air and in dusty environments. The polarity of the charging depended on that of the ambient electric fields.
2. A surprising finding was that a CH-53E helicopter, operating in the negatively-charged dust clouds that it raised from the earth, charged positively by emission of negative charges in the exhausts from its engines.
3. A servo device for controlling the charging of a helicopter was designed and constructed. Its features for sensing charge intensification were sufficiently novel that it and the charge control system have been patented by the Naval Research Laboratory Patent Counsel (patent #4,980,795, issued 25 December 1990) (Moore *et al.*, 1990b).
4. The charging tendencies of all of the aircraft were controlled by shielding the engine exhausts from external electric fields then using the servo device to create an internal field with the application of voltages to an electrode immersed in the exhaust gases. This technique was successful even when the helicopter raised strongly charged dust clouds.

RECOMMENDATIONS FOR MINIMIZING THE CHARGING OF EXISTING HEAVY-LIFT HELICOPTERS

1. To overcome the natural charging tendencies of a hovering helicopter, we recommend that its engine exhaust gases be electrostatically shielded from external electric fields and that the fields within the shields be controlled by the application, to an internal electrode, of an appropriate voltage with the same polarity as that of the undesired charge on the aircraft.

2. The design for an op nized shield-and-electrode configuration should be determined after more extensive measurements on operating, heavy-lift helicopters than have been possible in these initial field experiments.

   Our work thus far has been to identify the source of the charging and to explore the possibilities for its control. With the identification of a dominant charging process accomplished and with a means for its control developed and tested, the appropriate engineering studies now should be undertaken so that an airworthy charge-control system can be designed and built.

3. An operationally useful system is needed for sensing the electric field at the location where ground personnel will first contact a hovering helicopter.

   As discussed in the text, reduction of the net charge from the airframe is not sufficient to prevent electrical shocks when ground personnel contact conducting parts of an isolated aircraft that is hovering in air containing space charges. To minimize shocks to approaching ground persons, the strength of the electric fields on the portion that they first touch must be maintained at low levels. This may be accomplished by use of a an electric field sensor at this location together with a fast-acting charge control system. Another approach that has been suggested involves sensing ground potential relative to the aircraft by use of a weakly conducting line, a field meter and the charge-control system.

CHARGE CONTROL DESIGN CONSIDERATIONS FOR FUTURE HEAVY-LIFT HELICOPTERS

1. Since the techniques used to reduce the infra-red signatures of the engine exhausts will affect the electrical conductivities of the gases when they emerge into the atmosphere, efforts should be made to utilize this effect so as to decrease the natural charging tendencies of the new aircraft.

2. In procuring new helicopters that will be used under conditions where natural electrification can cause problems, provision should be given to shielding the engine exhausts in the basic design of the aircraft rather than depending on ad-hoc retrofits.

1 INTRODUCTION

A helicopter isolated from the earth often acquires electrical charges which can be dangerous to ground personnel who contact the aircraft. The widely held explanation for the cause of helicopter electrification has been that it is a result of collisions between the rotor blades and dust particles in the surrounding air. This explanation has not been accepted universally because significant electrification has been observed with helicopters operating in the absence of any significant dust and other atmospheric particles. For example, strong electrification has been reported by Marine Corps pilots when large helicopters have landed on the decks of aircraft carriers at sea where little dust and no sea spray was present.

In the earlier study under ONR Contract N00014-84-K-0623, Brook and Moore (1986) found that electric currents of several microamperes flowed into the air from an aircraft engine mounted on an isolated test stand exposed to the atmosphere. These currents were carried by ions in the electrically-conductive engine exhaust gases which were under the influence of the ambient electric fields around the exhaust port. The conductivity of these gases was created by ionization processes during the combustion of fuel in the engine and it persisted for an appreciable time after the gases emerged from the exhaust.

Subsequent measurements with isolated, small Hiller and Hughes helicopters (with their exhaust ports near the top of the fuselages) indicated that these aircraft lost negative ions in the exhaust gases acted upon by the fine weather, atmospheric electric fields which caused negative ions to rise away from the aircraft. This loss of negative charge from an initially neutral aircraft left an equivalent positive charge on the airframe which developed potentials of about 1 kV with respect to the earth as a result.

The finding that the ambient electric fields affect the electrification of a helicopter was supported when, on two occasions, thunderclouds formed upwind and produced foul-weather polarity electric fields under which positive ions move upward. Under the foul-weather fields, the isolated helicopter became strongly charged with the negative polarity by loss of positive ions in the exhaust. This condition persisted until the storms passed by. Afterward, the aircraft charge reverted to the positive polarity as the atmospheric electric field returned to its normal, fine-weather polarity and negative ions again were emitted in the exhausts.

These observations suggested that the emission of charge in the exhausts might be controlled by electrostatically shielding the hot gases from the external fields (while the gases are still electrically conductive) together with the application of suitable control voltages to an electrode immersed within the exhaust stream inside the shield. Application of a negative voltage to the electrode creates the electric field that causes the emission of negative ions in the exhaust gases while a positive voltage causes positive ions to leave the aircraft. To use this approach, a servo control was designed that used the polarity and magnitude of charge at a given location on the airframe to apply the appropriate control voltages to the exhaust electrode.

Flight tests of this technique were carried out using small helicopters operating from Socorro airport (Brook and Moore, 1986). Various versions of the servo device were used successfully to control the charging of Hiller and Hughes helicopters hovering over dusty soil around the

Table 1: List of field trips for the study of CH-53E helicopter charging processes.

Dates	Location	USMC Heavy-lift Squadron	Helicopter Number	Number of Ground Tests	Report Number
01–06 Nov. 87	MCAS, Tustin, CA	HMH-466	02	6	3
08–12 Feb. 88	MCAS, Tustin, CA	HMH-465	00, 14, 16	7	4
06–13 Jan. 89	MCAS, Tustin, CA	HMH-466	65	9	5
16–22 Mar. 90	Davis-Monthan AFB, Tucson, AZ	HMH-465	21	7	6

airport. These results led to the first task under Contract N00014-87-K-0783 under which tests of the charge control technique were to be made on Marine Corps heavy-lift helicopters which have much more powerful engines and move more air than do the small helicopters on which the first studies were made.

2 MEASUREMENTS ON MARINE CORPS CH-53E HEAVY-LIFT HELICOPTERS

In the period between November 1987 and March 1990, four field trips were made to military bases during which measurements were made on the electrical charging characteristics of CH-53E helicopters. The dates, locations and other pertinent information on these trips are listed in Table 1. The results obtained from these trips were described in a series of reports which are listed in the appendix. Our findings from these studies are summarized in the following:

2.1 Measurements of the electrical conductivity of CH-53E engine exhaust gases

Since each of the three engines on a CH-53E helicopter can deliver about 4380 hp, far more than the 300 hp supplied by the Hiller helicopter used in our initial studies, measurements of the CH-53E exhaust gas conductivities were needed to determine the sizes of the electrostatic shields that would be necessary. For these, we fabricated a high-temperature, conductivity-measuring cell, consisting of the Gerdien capacitor described in Report No. 3 (Moore and Hignight, 1988) and used it in the three field trips to the Marine Corps Air Station in Tustin, California.

With the Gerdien capacitor mounted on a long boom that moved across the exhaust stream at various distances from the exhaust stack, we found that the initial polar conductivities of the exhaust gases emerging from the exhaust stacks on #1 and on #3 engines were about 500 pico siemens per meter. (The siemen is the International System unit for electrical conduction measurements and has dimensions of amperes/volt.) The values we measured indicate that positive and negative gas ions were present in concentrations of about 10 million per cubic centimeter of exhaust gas. As a result, there is no difficulty in explaining electric current flows of several microamperes in such high conductivity gases under the influence of external electric fields. A free charge immersed in a gas with these conductivities would be neutralized by ohmic conduction processes in about 20 ms.

We found, however, that the gas conductivities decreased rapidly downstream as a result of dilution with ambient air and of ion depletion by recombination and by attachment to aerosols. Typically, the conductivity decreased by e-fold (by 63%) in a distance of about 30 cm when the helicopter rotor was creating a downdraft.

Similar measurements around the exhaust from #2 engine indicated appreciably lower initial conductivities; in some of the measurements, the gas conductivities near the exhaust port were about 50 pS/m, about 1/10 that found at the other two exhausts. This lower value may be a result of the faster mixing of ambient air into the exhaust from #2 which is nearer the rotor and which has a greater cross-sectional area than the other exhaust stacks.

Table 2: Measurements of the natural charging of a CH-53E helicopter while the rotor was stationary in clear air (one engine, usually #3, operating).

Shield Length (inches)	Limiting Potential Achieved (kV)[a]	Ambient Wind (m/s)	Date	Time (PST)	Helicopter Number	Report	Page
None	+2.0	Near calm	11/03/87	1540	HMH-466 #02	3	10
None	+1.8	Near calm	11/04/87	1116	HMH-466 #02	3	12
36	+35	13[b]	01/12/89	1340	HMH-466 #65	5	16
36	+1.3	3	03/20/90	1241[c]	HMH-465 #21	6	20
36	+1.0	4	03/21/90	0916[c]	HMH-465 #65	6	26
71	+2.0	5[b]	11/06/87	1625	HMH-466 #02	3	21
71	+3.1	4[b]	02/09/88	1526	HMH-465 #00	4	23
71	+0.9	Near calm	02/12/88	1435	HMH-465 #14	4	38

[a]Helicopter potential relative to the earth.

[b]No anemometer was available; wind speed was estimated.

[c]MST

Note: The limiting potentials developed between the helicopter and earth is these experiments were achieved when the charging currents were balanced by leakage currents that were driven by the potential differences and the associated electric fields. With a given experimental configuration, higher limiting potentials usually indicate either larger charging currents or less easily activated leakages. In our tests, the ultimate peak potentials were limited by dielectric breakdown and by sparking over the surfaces of the insulators that were used. On the other hand, limiting potentials of up to +140 kV were reported by Pechacek *et al.* (1985) on hovering CH-53E helicopters which had much greater electrical isolation than was possible in our ground-based tests. Pechecek *et al.* (1985) suggested that corona discharges from the tips of the rotor blades limited the potentials that they measured; sparking was not reported as a limiting factor in their measurements.

In these tests, we also measured the exhaust gas temperatures with a type K thermocouple and the exhaust gas speed with a Pitot tube and a differential pressure sensor. Exhaust gas temperatures were around 300 °C about 1/2 m downstream from the exhaust stack where the calculated exhaust speed was about 30 m/s. The gas temperature and its speed decreased rapidly with distance from the exhaust stack with the entrainment of environmental air.

2.2 Electrostatic shields around the engine exhausts

The downdraft of up to 40 m/s created by the rotor interacts so strongly with the flow of the exhaust gases that it is not possible to construct a simple, fixed electrostatic shield which can screen the hot gases under all of the various engine power and rotor pitch settings that are used in hovering. On the basis of our measurements which indicated rapid decreases in conductivity with distance from the exhausts, our best approach was to construct open-ended cylinders of wire screen that were placed in an inclined attitude around the exhaust gas streams as they emerged from the exhaust stacks. As shown in the sketch in Appendix A, the wire-mesh cylinders were fabricated of "hardware cloth" with 0.5-inch square holes in the mesh. The screens were rolled into 1-meter diameter cylinders; their shape was maintained by mounting them on rings that were rolled from aluminum channel, 1.25 inch by 3/8 inch. In the initial experiments, the shields had a length of 1.8 m (71 inches); in later tests, shield lengths of 0.9 m (36 inches) were used.

These shields were mounted around the exhausts of the #1 and the #3 engines of various CH-53E helicopters using glass-fiber epoxy rods supported by maintenance stands. This arrangement was used to avoid hanging any load on the aircraft and to isolate the shields electrically both from the earth and from the aircraft so that any currents flowing in the shields could be measured. The cylinder axes were inclined at an angle of about 25 degrees below the horizontal in an effort to contain the exhaust gases as they were deflected by the rotor-induced downdraft.

During these tests, the large, elliptical exhaust port from #2 engine was not shielded and we made no attempt to control its charge emissions.

2.3 Measurements of the natural charging of a CH-53E helicopter with the rotor stationary

Before beginning the charge control experiments, we measured the natural charging of a CH-53E helicopter. After this, observations were made as to how the aircraft charged with the electrostatic shields around the exhausts but with no control being attempted.

For both these and the subsequent charge-control experiments, we isolated the test helicopter from the earth by rolling it up onto 2 inch thick polyethylene slabs under each set of the landing gear wheels. The potential of the helicopter relative to earth was measured by a special, electric-field-measuring voltmeter that required no current and therefore placed no load on the electrostatic generating capability of the helicopter charging process. (The

Table 3: Measurements of the natural charging of a CH-53E helicopter while the rotor was causing downdraft in clear air (one engine, usually #3, operating).

Shield Length (inches)	Limiting Potential Achieved (kV)	Estimated Ambient Wind (m/s)[a]	Date	Time (PST)	Helicopter Number	Report	Page
None	-36[b]	Calm	03/11/87	1551	HMH-466 #02	3	11
None	+34[c]	2	02/09/88	1529	HMH-465 #00	4	23
None	-38[b]	2	02/09/88	1538	HMH-465 #00	4	23
36	-36	15	01/12/89	1400	HMH-466 #65	5	16
36	-41	3	01/13/89	1035	HMH-466 #65	5	21
36	-44	7	01/13/89	1430	HMH-466 #65	5	24
71	-20	2	11/06/87	1625	HMH-466 #02	3	31
71	-20	2	01/10/89	1400	HMH-466 #65	5	12
71	-32	12	01/11/89	1240	HMH-466 #65	5	14

[a]No anemometer was available; the wind speed was estimated.

[b]Limited by sparking.

[c]Initial excursion after rotor started turning.

details of this voltmeter are described in Reports #3 and #4 [Moore *et al.*, 1988]; it is based on an earlier device used by Douglas and Nanewicz [1973]).

The first measurements were made with the aircraft on a dust-free, concrete hard-stand at Tustin in clean air, during fine weather with low ambient winds. When one of the helicopter's engines was started with the rotor locked, we found that the aircraft emitted currents of about $-2\ \mu$A into the air and charged slowly to positive potentials of about 1000 to 2000 V (about as the Hiller helicopter had done in Socorro). On one occasion, however, when a strong Santa Ana wind was blowing, an isolated CH-53E helicopter with the rotor stationary charged to about +35 kV immediately after it was ungrounded. A summary of these experiments is given in Table 2.

2.4 Measurements of the natural charging of a CH-53E helicopter with the rotor turning in clear air

During the clear air tests at Tustin, the electrification developed by each helicopter increased greatly whenever the turning rotor developed a significant downdraft. On some occasions, as shown in Figures 1 and 2, the helicopter's positive charge initially increased after the rotor began to turn. As the downdraft intensified, however, the helicopter always charged negatively and quickly developed potentials, relative to earth, ranging from about -20 kV to -44 kV. Thereafter, the charging processes maintained the aircraft potential around these levels. Each of the five different CH-53E helicopters tested at Tustin charged negatively in this fashion under the influence of the downdraft caused by the rotor. From the results listed in Table 3, it appears that the greatest negative charging occurred when either the ambient winds were the strongest or when the shielding was the least. On the other hand, this charging was lower when the largest shields were used and the surface winds were near calm.

Currents ranging from +8 to +12 μA flowed into the air when the aircraft charged negatively in a rotor-induced downdraft with an unshielded engine exhaust. Use of an electrostatic shield around the exhaust reduced these flows: charging currents of about +6 to +7 μA measured when a 36-inch-long shield was used while values between +4 and +5 μA occurred with the 71-inch-long screen cylinders around the exhaust.

We were not able to determine the trajectories of the ions in the exhaust gases during the period that the aircraft charging reversed polarity. From the charging behavior, however, it appeared as if the onset of the downdraft transported the exhaust gases and the initial negative charges above the aircraft in a toroidal circulation. The downdraft apparently reversed the polarity of the electric field acting on the exhaust, and induced positive ions to be emitted in the exhaust gases, thus charging the aircraft negatively. Unfortunately for this hypothesis, there was no subsequent change in the polarity of the aircraft as positive charges entered the rotor-induced circulation and presumably were carried above the helicopter.

Whenever the aircraft was discharged by grounding it briefly, immediately afterward it recharged quickly back toward the earlier strong negative potential at exponentially decreasing rates with time constants of as low as 6 seconds. Examples of the recharging are

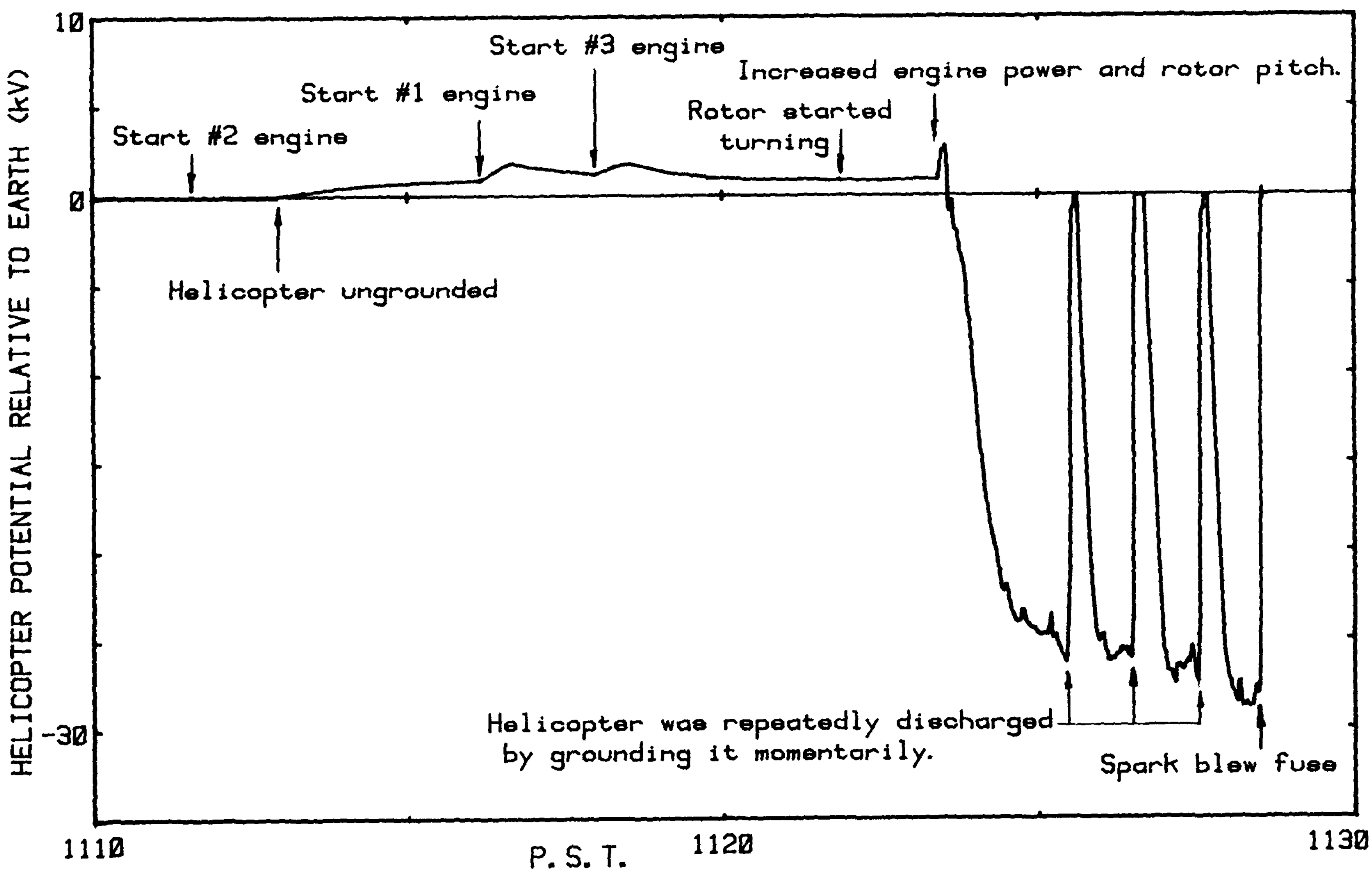

Figure 1: The potential of an isolated, ground-based CH-53E helicopter allowed to charge naturally with all three engines operating in clean air (MCAS, Tustin, CA, November 4, 1987).

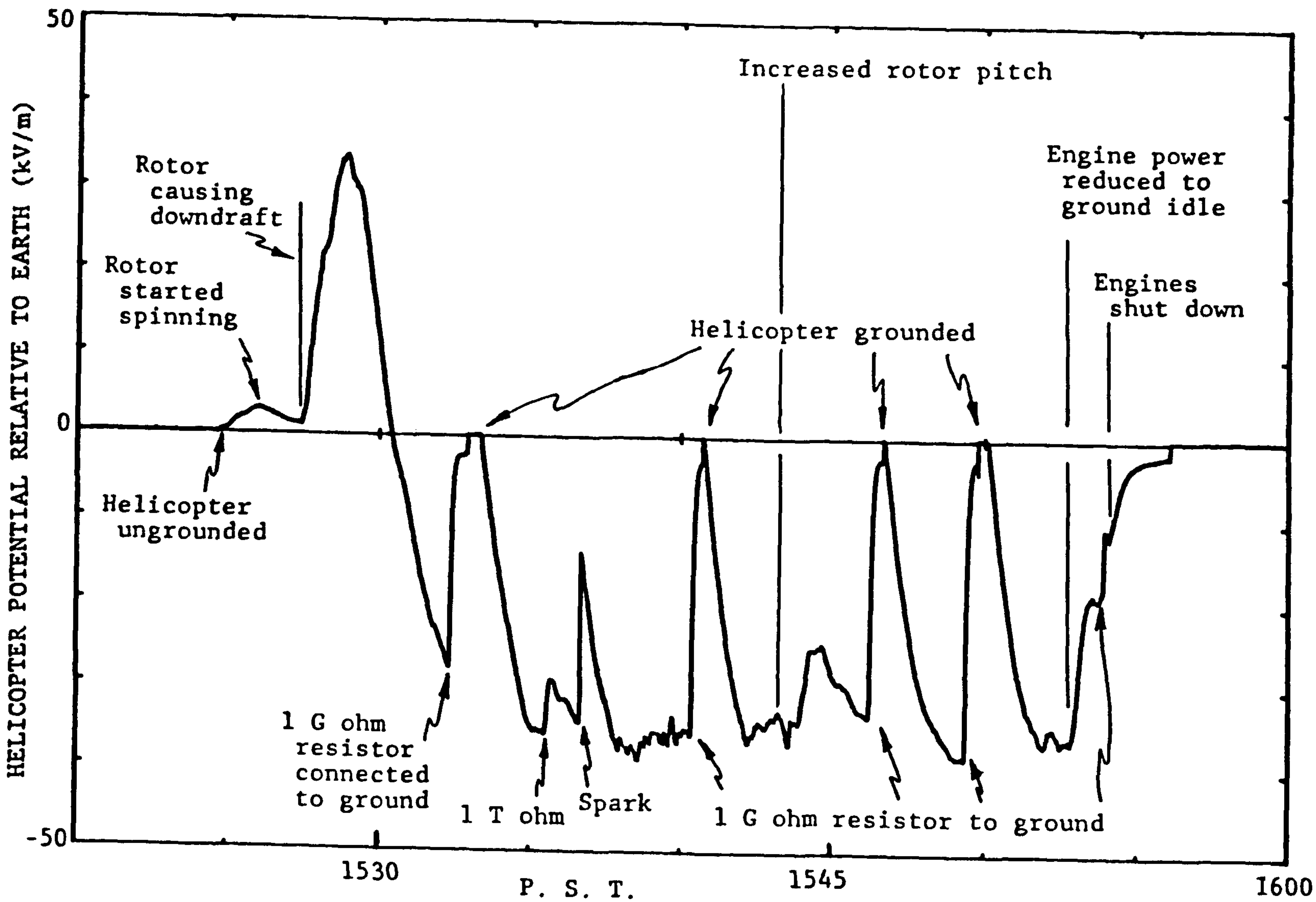

Figure 2: The potential of an isolated, ground-based CH-53E helicopter allowed to charge naturally with all three engines operating in clean air (MCAS, Tustin, CA, February 9, 1988).

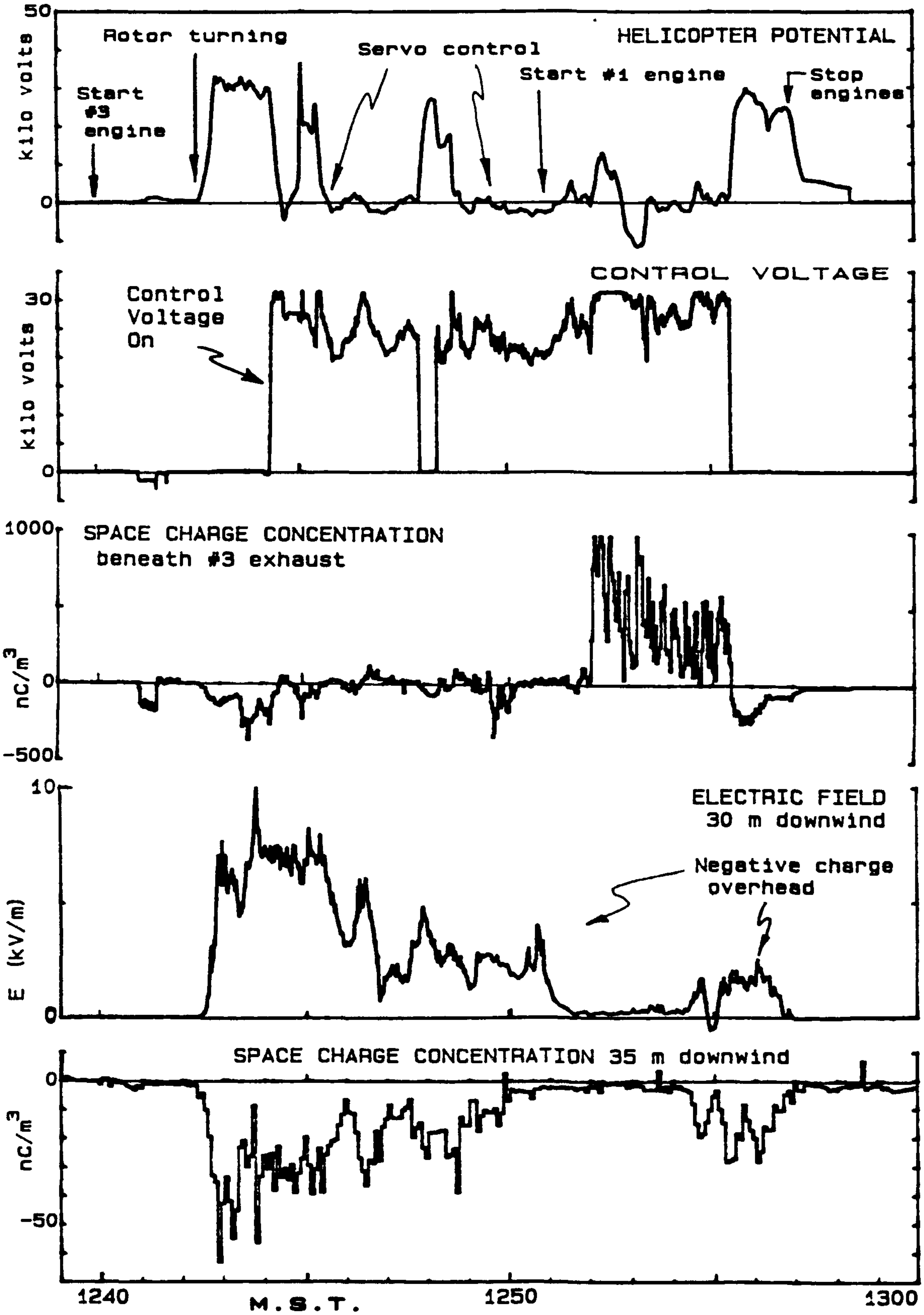

Figure 3: Illustration of the natural charging in dusty air followed by a test of the helicopter charge-control system. The ring electrode was mounted 3 inches from #3 engine exhaust stack (Tucson, March 20, 1990).

shown in Figures 1 and 2. It is interesting that, in Figure 1, the insertion of a high resistance of the order of 10^{12} ohms (1 T ohm) between ground and the isolated helicopter (to measure the charging currents) seriously loaded down the electrostatic generating process, causing the helicopter potential to decrease by about 20%. A simplistic interpretation of this result is that the source resistance of the equivalent electrostatic generator was of the order of 2×10^{11} ohms but as Pechacek *et al.* (1985) noted, the charging seems to be non-linear and the source characteristics probably are not constant.

2.5 Measurements of the natural charging of a CH-53E helicopter with the rotor turning in dusty air

A different charging regime was observed in the dusty environment of the last set of experiments during March, 1990 (Report No. 6, Moore *et al.*, 1990a). The test CH-53E helicopter (#21) was moved to an unpaved, dusty area at Davis-Monthan AFB in Tucson, where it was electrically isolated on polyethylene slabs as previously done at Tustin. The exhausts from engines #1 and #3 were shielded with 36-inch-long cylindrical screens. After engine #3 was started, the helicopter charged to about +1200 V while its rotor was stationary (as did the other CH-53E aircraft in Tustin) but, after the rotor was released and began to raise negatively-charged dust, the aircraft in Tucson became even more positively charged to potentials of around +30 kV during three different tests. These results are listed in Table 4. An example of this behavior is shown in Figure 3 around 1242 MST.

[It is worth noting here that two CH-53E helicopters hovering in dust clouds at Twenty-nine Palms, California were observed to charge to positive potentials in excess of +100 kV by Pechacek (1985). The polarity of any charge on their dust was not reported so that it is not clear that their aircraft charged exactly as did the helicopter at Tucson.]

The negative charges on the dust at Tucson appeared to be a result of contact electrification processes operating when the dust was lifted from the ground. Negatively-charged dust in concentrations of about -1 nC/m^3 was stirred up when we walked around and when puffs of wind raised small dust clouds. On the other hand, when the rotor-induced downdraft raised large dust clouds, charge concentrations of the order of -50 nC/m^3 were measured in a Faraday cage located 35 m downwind. While enveloped in these negatively-charged dust clouds, the helicopter always charged positively. This is surprising because collisions of negatively-charged particles with the rotor and the ingestion of negatively-charged dusty air into the engine during combustion could have made the aircraft charge negatively but this never occurred when dust enveloped the aircraft while the rotor turned.

One source that has been suggested for the positive charging of the helicopter is that the dust particles raised from the earth acquired even more negative charge by contact electrification upon colliding elastically with the rotor. While some of this may have occurred, it seems unlikely to be the dominant charging process. Among the reasons that support this opinion are the measurements made by Brook and Moore (1986) on an isolated rotor blade turning into very dusty air on the whirl tower at the Naval Air Repair Facility, San Diego. In these tests, finely-divided road dust was released into the air above the rotor and the charges it carried were measured. The blade charged *negatively* in most of these tests although the

Table 4: Measurements of the natural charging of a CH-53E helicopter while the rotor was causing downdraft in dusty air (#3 engine operating alone).

Shield Length (inches)	Limiting Potential Achieved (kV)	Ambient Wind (m/s)	Date	Time (PST)	Helicopter Number	Report	Page
36	+33	3	03/20/90	1245	HMH-465 #21	6	20
36	+30	4	03/21/90	1201	HMH-465 #21	6	28
36	+33	5	03/21/90	1331	HMH-465 #21	6	30

charge polarity fluctuated, with positive charging observed briefly in the course of some tests. The maximum currents measured were about 0.25 μA but the average currents were much less. If we extrapolate the peak current observed for the single blade to the seven blades on a CH-53E, a current of about 2 μA might be expected but the preferred polarity was opposite to that observed in Tucson.

While the results from the whirl tower studies do not give much support for explanations of helicopter charging by collisional processes, observations of intense charging of fixed-wing aircraft flying through volcanic dust have been reported (Anderson *et al.*, 1965). There is no question about the occurrence of charge transfers during momentary contacts between dissimilar materials; the problem here is to identify the dominant processes causing helicopter electrification. The measurements in Tucson suggest that the helicopter charged positively by the export of negative charges on the exhaust gases into the surrounding, negatively-charged dust cloud: A Faraday cage, mounted below the exhaust from #3 engine, gave indications of negative space charges with concentrations up to -200 nC/m^3 when the downdraft blew exhaust gases through the cage.

2.6 Discussion of the natural charging of a CH-53E helicopter with the rotor turning

From our studies, there seems to be a feature that is common to the charging in clear air and to that in dust. When the natural charging associated with rotor-induced downdrafts for the clean air measurements is compared with that for the dusty situation, in both cases the *polarity* of charge developed on the airframe during a downdraft was that of the external electric field. We found that the aircraft charged negatively in the presence of a downwardly-directed (i.e., a negative, fine-weather) electric field whereas the airframe acquired positive charges when the negatively-charged dust around the helicopter created a positive (i.e., an upwardly-directed) field. The details of these findings are discussed in Report No. 6 (Moore *et al.*, 1990a) and in Moore *et al.* (1991, pages 29-6 and 29-7).

There is another factor associated with the charging to be considered: the high potentials developed by the charging of these helicopters are ultimately limited by leakage currents of some sort. In some of our tests, sparking across the insulators prevented further increases in helicopter potential while, in others, the charging was limited more smoothly by leakages driven by the strong electric fields produced by the charge on the aircraft. Dr. Clyde Richards (private communication, 1984) and Pechacek *et al.* (1985) both suggested that "corona discharge," the luminous ionization of air around sharply-pointed, highly-charged conductors, can cause electrical leakage from an isolated helicopter when its rotor is turning. The blade tips are well-exposed, highly-curved, and in a region of aerodynamically-lowered atmospheric pressure. All of these favor the ionization of air molecules and the flow of currents into the atmosphere surrounding a highly-charged conductor.

Some of the pilots who worked with us described earlier observations, during flights at night, of luminosities similar to St. Elmo's fires at the tips of the rotor blades. (St. Elmo's fires are coronas caused by electrical discharges into strong electric fields.) They reported that they had seen such luminosities on some night flights when no dust was present. When such luminosities appear, they provide evidence that strong ionization and atomic excitation

are occurring and that charges are flowing into the air under the influence of the local electric fields. Charge emissions of this type, however, can be appreciable even though the levels of ionization are too low for the creation of noticeable luminosities. The luminosities and the current limiting that is observed suggest, therefore, that the blade tips provide a region, similar to that of the engine exhausts, where charges flow into the air and affect the electrification of the aircraft.

After participating in the 1984 helicopter measurements by Pechacek et al. at Twenty-nine Palms, our associate, Dr. Richards, suggested to us that many of the charges flowing into the air from corona at the rotor tips are caught in the local downdraft and are carried downward, below the aircraft. In his view, the transport of this charge beneath the helicopter would intensify the electric fields causing the corona thus making the helicopter act as an electrostatic generator with the downdraft doing work on the charges emitted from the rotor.

Evidence that may support Richards' hypothesis appeared during the February 1988 measurements at Tustin when we briefly connected a 10^{12} ohm resistor between an isolated, naturally-charged, negative CH-53E and earth (Moore *et al.*, 1988 [Report No. 4, Figure 15, 1535 PST]). Immediately afterward, a transient puff of negative space charge was detected downwind of the aircraft above two different electric field mills. The helicopter appeared to be the source of this charge which was surprising because, prior to the connection, our measurements indicated that the helicopter had been giving up positive charges into the air and these emissions had charged the aircraft to a potential that was limited at about -35 kV. As discussed above, connection of the high resistance from the aircraft to earth decreased the potential (to about -29 kV) but, after the resistor was removed, the aircraft recharged with the continued emissions of positive charge until a large spark occurred. We suspect that the negative charges originated in the limiting leakage current which was revealed only when the helicopter potential was changed abruptly by connection of the weakly-conductive resistor to earth. The leakage current may have come either from the rotor tips or from the engines, depending on which source was emitting the positive charges.

Although Richards' hypothesis may aid in explaining the puzzling, clear-air observations in which the helicopter potential reversed polarity and intensified after onset of the rotor-induced downdraft, there is not enough information from these field studies for an evaluation of the interactions between the emissions from the rotor and those from the engines. However, the idea of two different charge sources that are competing for the helicopter electrification is also supported by the observations (as shown in Figure 2) of the strong charging, first with positive polarity followed by negative polarity immediately after the onset of the rotor-induced downdraft.

We turn now to consideration of techniques to reduce the natural electrification of helicopters. While we can not easily control or modify any corona discharges from the rotor tips, reduction of the charging by the engine exhaust gases is feasible by control of the electric fields acting on them.

2.7 Apparatus for controlling the electric fields within the electrostatic shields

To control the electric fields acting on the exhaust gases, an isolated metal electrode, to which various voltages were applied, was placed within the electrostatic shield around #3 exhaust. Degradation of the electrode's isolation by carbon deposits from the exhaust was a problem in our early experiments but was eliminated, in the later tests, by supporting the electrode on shielded porcelain insulators located upstream of the exhaust port.

Various electrode configurations were used in these studies. In some tests, the electrode consisted of a 18-inch square screen placed across the exhaust gas flow around 12 inches downstream from the exhaust stack. In other tests, a toroidal metal ring with an outer diameter equal to that of the exhaust stack (about 20 inches) was mounted about 10 inches aft of the stack exit so that the exhaust gases passed through the hole in the toroid.

The electrode was connected to a voltage controller through a silicone-rubber insulated, high-voltage cable. The controller circuit, shown schematically in Appendix A, consists of operational amplifiers and differentiators that drive the appropriate one of two 32-kV programmable power supplies (one of which delivers a variable positive voltage and the other a variable negative voltage). The high voltage power supply needed at a given time is connected to the control electrode by an internally-selected, high voltage relay. The output level of that supply is controlled either manually by the operator or automatically by the voltmeter that senses the helicopter potential. When the voltmeter provides the corrective input signal, the device operates as a servo controller of the aircraft potential. It was used in this mode for many of the tests and produced results such as are shown in Figure 3.

2.8 Charge control experiments

In all thirteen of our charge control tests with CH-53E helicopters, application of a sufficient voltage (having the same polarity as that of the undesired charge on the airframe) to the electrode immersed in the exhaust caused the export of the undesired charges in the exhaust gases. The voltage level necessary to reduce the aircraft charge to low values depended on the shielding that was used. When a 71-inch shield was mounted around the exhaust of the only engine operating, control voltages of around -14 kV were adequate to maintain the helicopter charge around the zero level during the clean air, ground turns at Tustin. Reduction of the shielding to a 36-inch-long cylinder required electrode voltages of about -20 kV for the same control in clean air and about $+25$ kV under dusty conditions. These results are summarized in Tables 5 and 6.

The quality of the charge control also varied with the electrode type and placement: poor control was obtained when the electrode was placed too far downstream (22 inches) in the 36-inch-long shield but quite good control was achieved at this location in a 71-inch-long shield and at 12 inch spacings in the shorter shield. The optimum shield-and-electrode configuration has not yet been determined.

Operation of #1 engine without a control electrode but with a 36-inch-long shield around its exhaust required the application of higher voltages to the electrode immersed in the

Table 5: The control voltages necessary to oppose the natural charging of a CH-53E helicopter while the rotor was turning in clear air (one engine, usually #3, operating).

Shield Length (inches)	Control Voltage Necessary (kV)	Electrode Spacing[a] (inches)	Date	Time (PST)	Helicopter Number	Report	Page
36	-22	12	01/13/89	1040	HMH-466 #65	5	21
36	-19	12	01/13/89	1055	HMH-466 #65	5	22
36	-18	8.7	01/13/89	1508	HMH-466 #65	5	25
71	-14[b]	36	11/06/87	1625	HMH-466 #02	3	29
71	-14[b]	36	02/11/88	1556	HMH-465 #16	4	35

[a]Distance from exhaust exit to electrode.

[b]Extrapolated to complete the charge neutralization from the maximum delivered from the high voltage power supply.

Table 6: The control voltages necessary to oppose the natural charging of a CH-53E helicopter while the rotor was turning in dusty air (#3 engine operating alone).

Shield Length (inches)	Control Voltage Necessary (kV)	Electrode Spacing[a] (inches)	Date	Time (PST)	Helicopter Number	Report	Page
36	+25	3	03/20/90	1250	HMH-465 #21	6	20
36	+20 to +13	10	03/21/90	0929	HMH-465 #21	6	24
36	~ +22	6.5	03/21/90	1209	HMH-465 #21	6	28
36	+16	10	03/21/90	1340	HMH-465 #21	6	30

[a]Distance from exhaust exit to electrode.

exhaust from #3 engine to counteract the natural charging of the aircraft. An example of this is shown in Figure 3 which is taken from Report No. 6, Figure 10 (Moore *et al.*, 1990a). During the period from 1243 to 1252 MST, the rotor was driven by #3 engine operating alone. Starting at about 1246 MST, the servo applied control voltages to the electrode in the shielded exhaust gases from this engine and maintained the helicopter potential (and therefore its charge) at low levels around zero with quite small emissions of space charges in the exhaust. The application of control voltages varying around +25 kV apparently was able to counteract the engine's natural tendency to emit negative charges under the dusty conditions. (This natural tendency for charge emission when the servo was not being used is demonstrated in the recordings of negative space charges beneath the exhaust from #3 engine for the times around 1243 MST and, again, after 1255 MST.)

On the other hand, after #1 engine was started around 1251 MST and joined #3 in driving the rotor, servo control voltages of up to +32 kV were required in the exhaust from #3 engine to counter the aircraft charging. Thereafter, high concentrations of positive space charges were detected in a Faraday cage beneath #3 exhaust, indicating that large emissions of positive charges were now required to offset the emissions of negative charges by the shielded, but uncontrolled exhaust from #1 engine.

During other tests, we found it possible to maintain the helicopter charge more-or-less around the zero level by the controlled emissions from #3 engine after #2 engine was started and operated without an electrostatic shield but the charge control was sluggish and was much poorer than when #3 engine operated alone.

In the first experiments with a CH-53E helicopter (Moore and Hignight, 1987 [Report No. 3, page 20]), attempts were made to control the helicopter charge by applying the control voltage directly to the isolated, electrostatic shield which was to be used as an "induction ring." A voltage applied to the shield would have caused the selective emission of ions in the exhaust having the polarity opposite that of the control voltage thus causing the aircraft to acquire charge having the control voltage polarity. This scheme worked well while the rotor-induced downdraft was weak but all control was lost in the strong downdrafts that developed after engine power and rotor pitch were increased toward operational levels. It appears that, under these conditions, the hot, still-conductive exhaust gases were blown downward, through the sides of the electrostatic shield. In this situation, the electric fields produced by applying control voltages to the cylinder had little effect on the selective export of ions in the exhaust emerging from the sides of the shield; the charge emissions now were controlled by the electric fields external to the shield that acted on the still-conductive gases emerging from the screen. It appears to us that use of an electrode within the shield offers better control under operational conditions.

3 STATUS OF THE PROBLEM

3.1 Summary

Although collisions between the rotor and dust particles have long been considered to be the source of helicopter electrification, these studies with CH-53E helicopters show that

emissions of charges in the exhaust gases under the influence of the local electric fields play a major role in charging an isolated aircraft. This finding is supported by the ease with which the natural electrification of an isolated helicopter could be reduced, even in highly charged dust clouds, by controlling the electric fields acting on the hot, electrically-conductive exhaust gases.

The limiting of the high potentials to which these isolated helicopters charged naturally, after the onset of the rotor-induced downdrafts, indicates that a potential-dependent leakage current develops and opposes the further charging of the aircraft. As suggested by Richards and by Pechacek *et al.*, the leakage may occur through corona discharges at the the exposed tips of the rotor blades after the aircraft becomes sufficiently charged.

Corona discharges from the rotor tips may interact, however, with the charging in another way than as leakage: As discussed earlier, Richards has suggested that ions emitted into the air from corona discharges at the blade tips may be caught in the local downdraft and carried downward, intensifying the charging of the helicopter. If this process occurs, it may take over as the primary electrostatic generator, relegating the engine exhausts to furnishing the limiting leakage currents. These considerations suggest that helicopter charging processes are much more complex than the simple collisional transfers of charge to a moving rotor that were proposed in earlier explanations of the electrification.

3.2 Charge control considerations

Despite the complexities associated with the natural processes and with charges emitted from the rotor, we had no trouble in taking control of a helicopter's electrification, even at the highest levels that we encountered, by applying the appropriate electric fields to the engine exhausts. Our best control of the local electric fields around the exhausts so far has been achieved by shielding them from external electric fields while imposing, within the shields, the appropriate field which would cause the export of the undesired airframe charges in the exhaust gases.

While the present shields and electrodes are useful in controlling the electrification of a ground-based helicopter, they are no more than research tools whose configuration must be made suitable for operational use. To make them airworthy and operationally practical, compromises in their design will be necessary. For example, these results suggest that, while better shielding was provided by the 71-inch-long screens, the shorter, 36-inch-long shield attenuated the external fields sufficiently that useful control of the natural charging of the #3 engine was achieved by use of the electrode in its exhaust. They also suggest that #1 engine should also be equipped with a similar shield and electrode to which the appropriate corrective voltage is applied by the same servo device used on the exhaust from #3 engine.

Since the exhaust gases from #2 engine had lower initial conductivities than those from engines #1 and #3, it may be that stable control of the helicopter charge can achieved by the rapid application of the proper corrective voltages to the electrodes in the shielded exhausts from #1 and #3 engines alone. A sufficiently rapid response to the onset of charging may eliminate the need for controlling the emissions from #2 engine; this possibility should be investigated in future work.

From our studies, we would expect that use of techniques aimed at a reduction of a helicopter's infra-red signature by the forced advection of cooling air would act also to reduce its electrical charging by the exhaust gases. While this may not be practical with the existing helicopters, it may be worth combining the techniques used to eliminate the two, potentially troublesome characteristics of the present aircraft in the designs of future helicopters. The introduction of ion-attaching chemical additives to the engine fuel has been suggested as another approach for the reduction of the exhaust gas conductivity but it introduces a new set of problems that would need to be evaluated carefully.

3.3 Shock hazards arising from atmospheric space charges

It should be pointed out that reduction of charges on a hovering helicopter can not eliminate all risk of shock to ground personnel who contact the aircraft. Making the helicopter charge-free at some point merely causes that portion of the aircraft to be at the same potential as the surrounding air. When strong space charges, such as those carried by dust, are present, the potential of the air at the helicopter level can be several tens of kilovolts relative to the earth. If a person on the ground touches an isolated helicopter that has been made free of net charge under these conditions, an appreciable current will flow as the helicopter potential is changed to that of the earth. When this occurs, the person in the conduction path to earth can receive a severe electrical shock.

This problem can be minimized if the servo-controlling electric field sensor is located on the part of the helicopter that is to be contacted first by the ground person *and* if the response of the charge-control system is sufficiently fast that it maintains this portion of the aircraft in a charge-free state as the ground person makes the contact.

Another means for the avoidance of shocks to ground personnel, suggested by Dr. Marx Brook at this Institute (private communication), would be to use a method similar to the technique for measuring the helicopter potential without drawing a sustained current. A weakly conducting, weighted line could hang down from a potential sensor on the aircraft so that a portion of the line touches either earth or ground personnel before anyone contacts a more conductive part of the helicopter. The resulting signal from the potential sensor to the servo would apply the necessary corrective voltages on the electrode in the engine exhausts so as to make the helicopter potential quickly become that of the earth. Ground personnel can then contact the aircraft directly without incurring a shock. The virtue of this approach is that it would not require good electrical contact with the ground because it is aimed merely at sampling ground potential and not at the direct discharge of the aircraft.

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Moore, C. B., J. J. Jones and S. J. Hunyady, 1991: "Charge Control Experiments on on a CH-53E Helicopter in a Dusty Environment," Proceedings of the 1991 International Aerospace and Ground Conference on Lightning and Static Electricity, Cocoa Beach, Florida, pages 29-1 to 29-9.

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APPENDIX A:
ILLUSTRATIONS OF THE CHARGE CONTROL APPARATUS

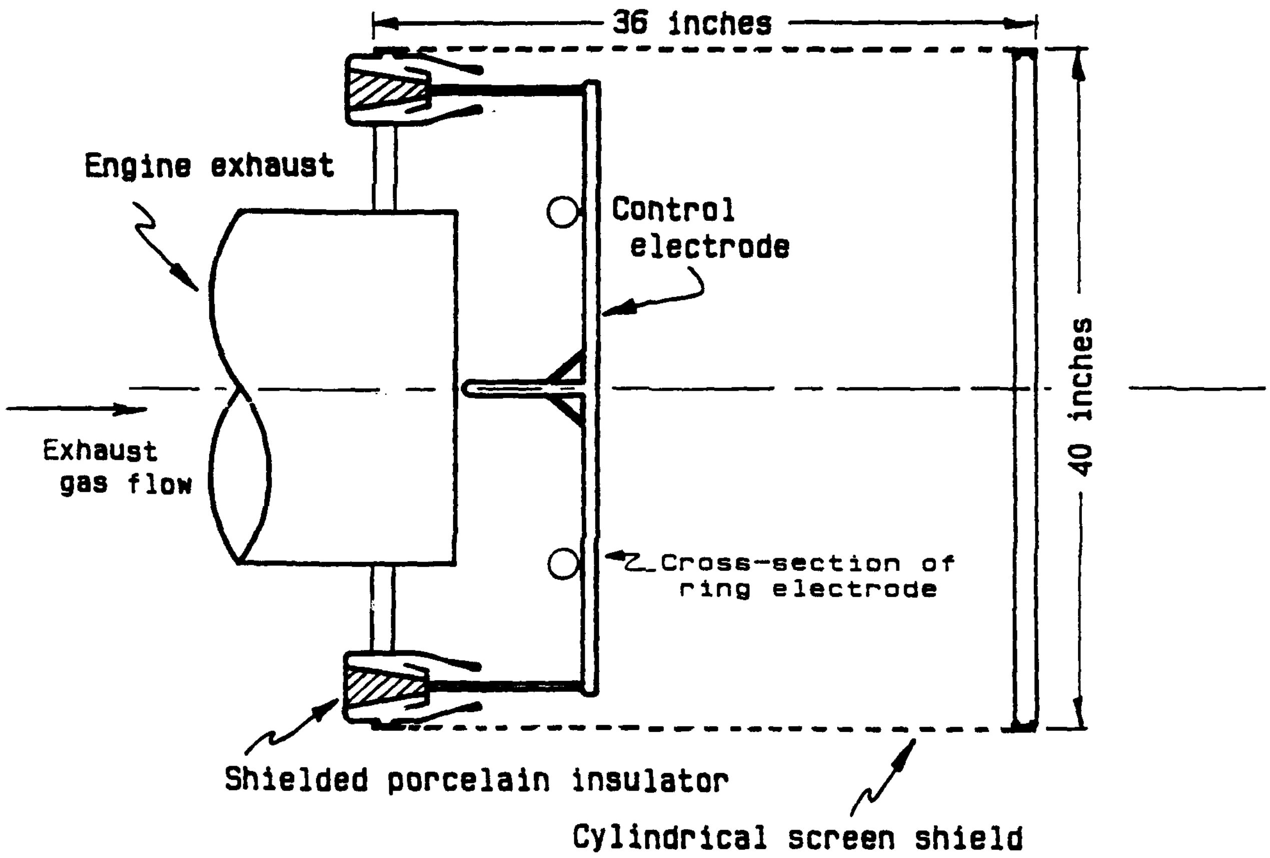

Figure 4: Sketch of the screen mesh cylinder used as an electrostatic shield around the exhaust of #3 engine.

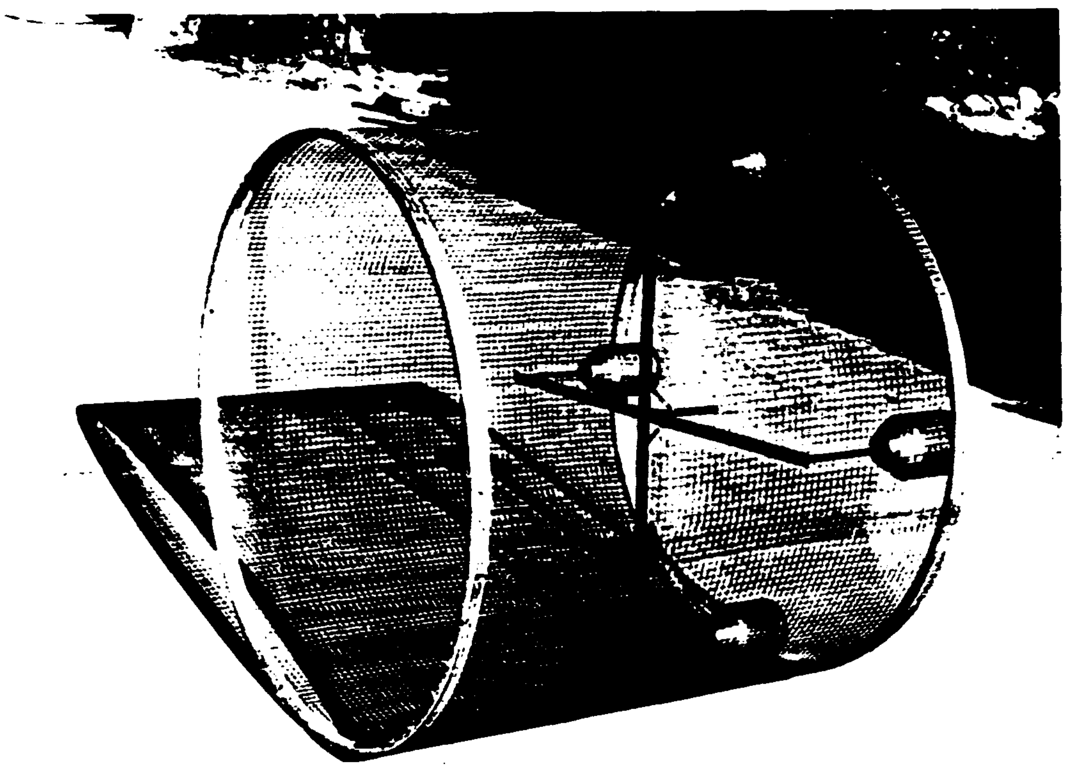

Figure 5: Photograph of the screen mesh cylinder used as an electrostatic shield around the exhaust from #3 engine.

Figure 6: Photograph of the equipment mounted near the exhaust from #3 engine. The electrostatic shield supported by fiberglas rods from a maintenance stand is shown at the top of the photograph. The Faraday cage used to measure space charge in the exhaust gases is mounted on the starboard "batwing" beneath the exhaust (Tucson, March 20, 1990).

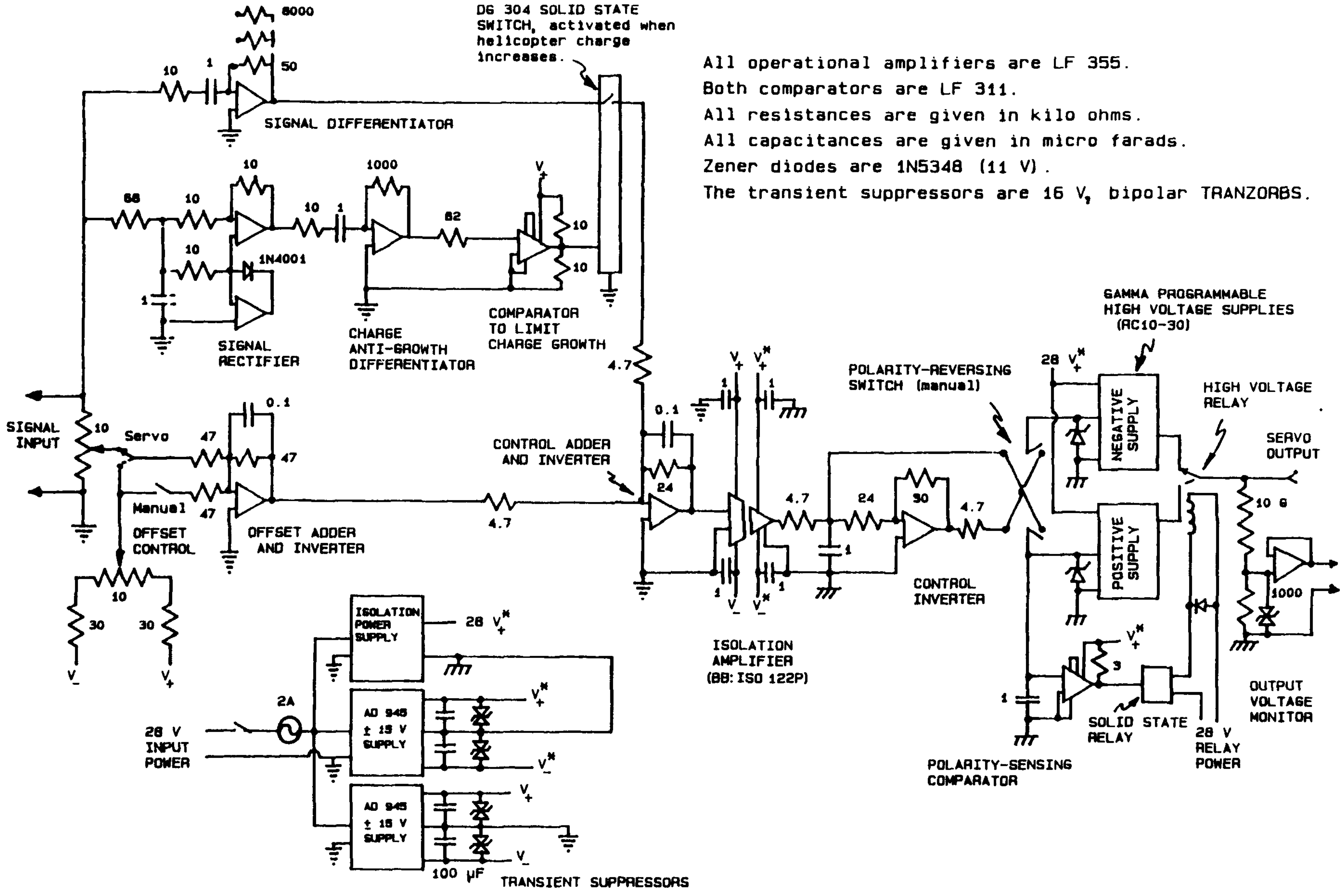

Figure 7: The circuit diagram for the servo control used to apply corrective high voltages to the electrode in the exhaust from #3 engine.

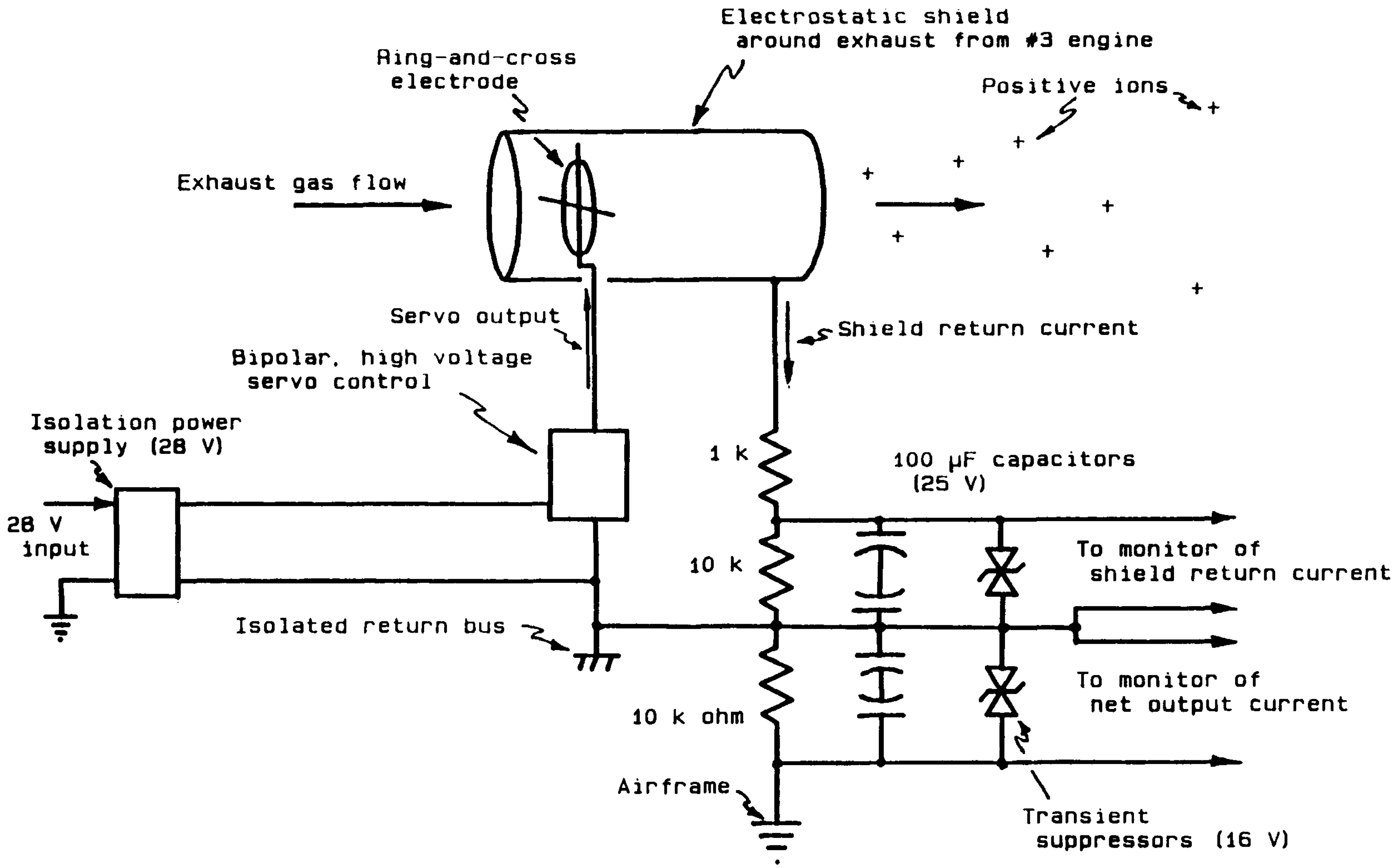

Figure 8: Diagram of the circuit used to measure the net output current from the servo control into the exhaust gases. The ndicated export of positive ions would occur if a positive high voltage were applied to the ring-and-cross electrode located within the electrostatic shield while exhaust gases were flowing.

APPENDIX B:

REPORTS AND PUBLICATIONS UNDER CONTRACT N00014-87-K-0873

Moore, C. B. and R. Hignight, 1988: "Studies of Helicopter Charging, Report No. 3, Measurements of the Interactions of a Large Helicopter with Atmospheric Electricity at the Marine Corps Air Station (Helicopter), Tustin, California, Nov. 2–7, 1987," Contract N00014-87-K-0783, 42 pages.

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Note: Copies of these reports and publications are available, on request, from the authors.